Near Field Linear Accelerators

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Abstract

In the context of accelerators needed in the 90's and beyond, we give a generalized view of "near field" accelerator systems. Performance requirements and some expected limitations are discussed and some important R/D topics are listed. No clear candidate for the "near field linear accelerator of the future" has yet emerged although a wide variety of potential candidates exist, among them the familiar rf linac.

Introduction

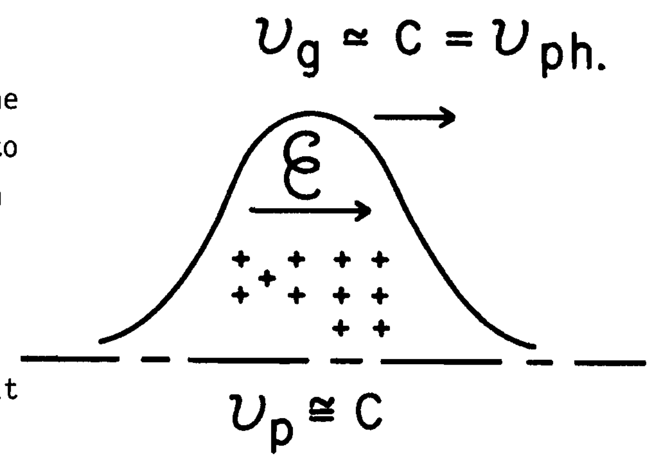


FIG. I

In a linac which uses a time dependent electromagnetic field as the basic accelerating agent, one tries to arrange the circumstance indicated in Figure 1. Ideally, a cluster of charged particles, co-traveling with a wave packet of electromagnetic energy, is accelerated continuously at the expense of the electromagnetic wave energy. The phase velocity of the longitudinal EM waves must be the same as the particle velocity for best effect. Best overall efficiency of energy transfer to the particles would obtain if the group velocity were also equal to the particle velocity. As outlined in the introductory presentation various stratagems for approximating this situation have been devised. It was shown that, using EM waves from a single source, no such circumstance can be arranged in free space, that is in the wave zone. It was also shown that if transverse EM waves impinge on a properly designed assembly of dielectrics or conductors, they can couple to longitudinal EM wave packets of useful phase velocity that can be present in the space near the material boundaries, that is in the near zone. The desired waves might be evanescent longitudinal waves on the surface of a dielectric sheet or dielectric or conducting grating or they might be evanescent or propagating longitudinal waves within a loaded waveguide structure.

Accelerator Characteristics

The near field devices known to date share many common features as shown in Figure 2. Low frequency electrical energy (or perhaps chemical energy) from a reservoir such as the 50-60 Hz power line is converted to EM energy, broad or narrow band, depending on the detailed accelerator design, by some "source." The source output is coupled to the near field zone where the accelerating is to be done, the "structure", by some sort of coupling network.

Sources in use or proposed are magnetrons, gridded power tubes, gyrotrons, gyrocons, klystrons, klystrons plus storage cavities, lasers, free electron lasers, ultra relativistic proton beam generators or pulse power sources; which one depends upon what frequency or frequency band is to be used. It is likely that meeting the challenge of higher energies with normal conducting structures will require sources with peak output powers in the GW range or higher.

Coupling networks might consist of arrangements of familiar transmission lines or waveguides or of mirrors and/or lenses.

The structure usually fills two roles: it supports the desired near zone accelerating fields and acts as a transformer, multiplying the fields generated by the source. The structure might take the form of a closed, loaded waveguide[1,2], or arrangements of dielectric slabs with or without metallic backing[3,4], or open gratings.[5,6] To make this picture a bit more concrete without too much loss of generality, we redraw Figure 2 in a way more suggestive of familiar apparatus in Figure 3. Here the source is depicted as a beam excited device, the coupling network is depicted as a waveguide plus mode converter at one end of the structure which is depicted to suggest a periodically loaded waveguide. If the beam excited source were a klystron or klystron plus Q-switched energy storage cavities[7] and the structure were indeed a closed, periodically loaded waveguide, Figure 3 would be a schematic drawing of the most familiar form of microwave linac. If the beam excited source were a free electron laser, as has been suggested[8], Figure 3 would represent the same accelerator operating at a much shorter wavelength. In the case of the closed structure, the waves introduced at one end from the source bounce back and forth within the structure, adding

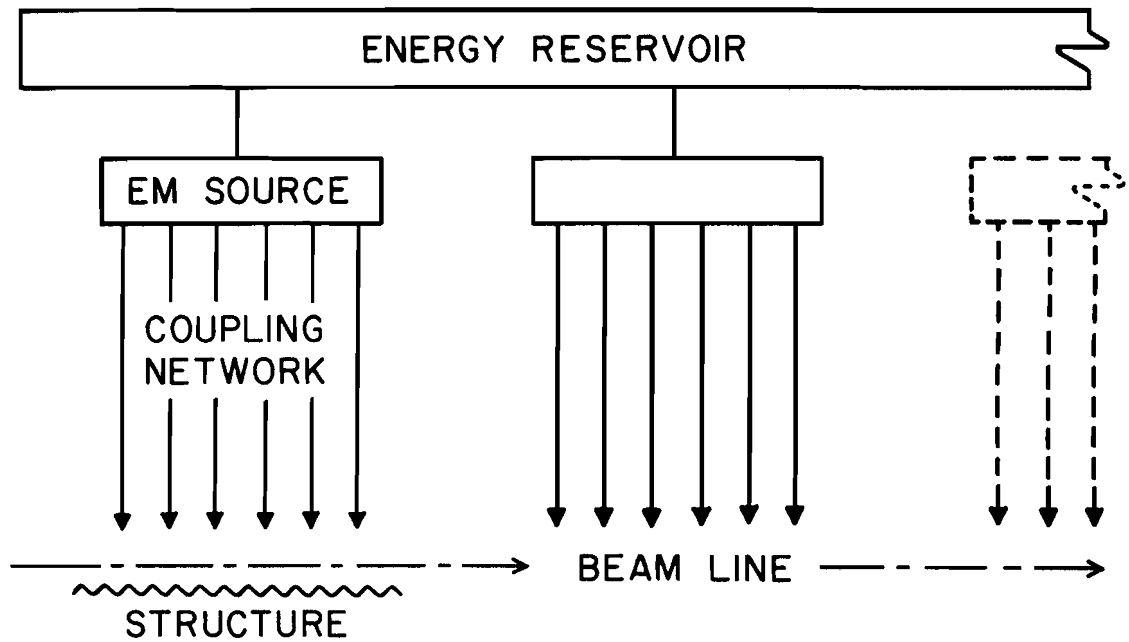


FIG. 2

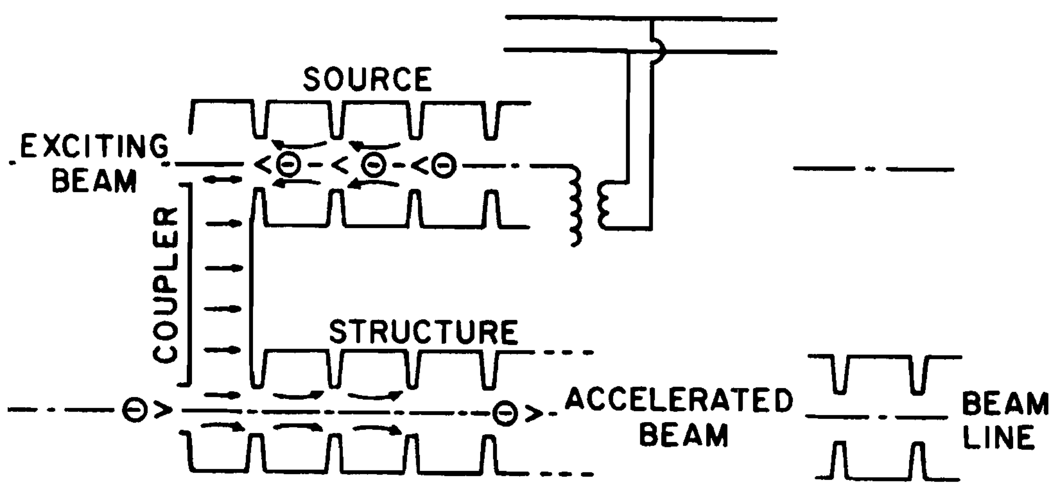


FIG. 3

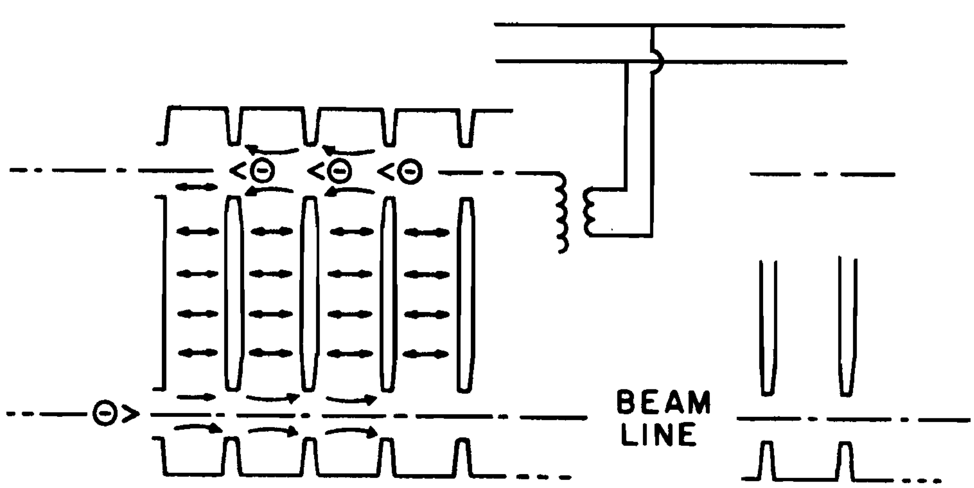
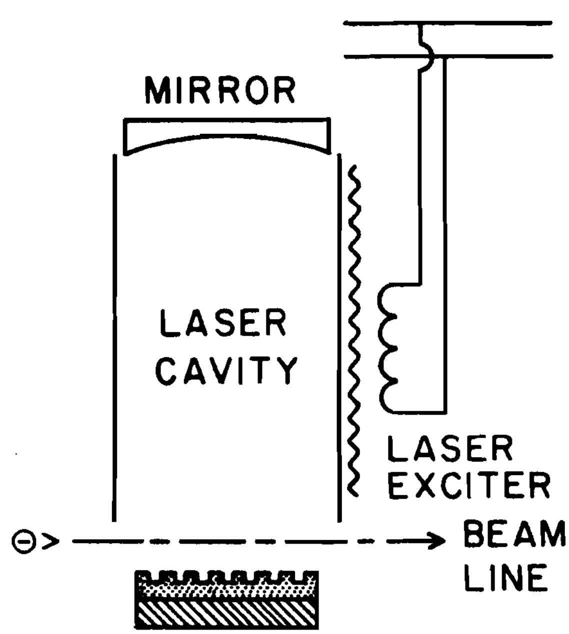


FIG. 4

constructively to produce the desired multiplication of field. The effective number of bounces is determined by the group velocity in the structure. A high group velocity corresponds to relatively few bounces and lower multiplication.

In Figure 4 we have redrawn Figure 3 with a one-to-one correspondence between cells (gaps) in the source device and cells (gaps) in the structure. Each source gap is connected to each structure gap by a transmission line. In this way we see a natural metamorphosis from the monochromatically driven linac to the broad band "wakefield accelerator"[9] in which the transverse chambers can be viewed as pulse transformers rather than cavities. Of course we can imagine Figure 4 as the cross section of a cylindrically symmetrical device formed by revolution about the center line of the high energy beam. The exciting beam might be annular or there might be a number of exciting beams arranged symmetrically about the accelerated beam axis. The transverse symmetry about the accelerated beam axis need not necessarily be circular. The transverse section could be elliptical with the exciting cylindrical beam and accelerated beam centerlines at the foci of the ellipse.[9] The exciting beam might also be made to pass down the same channel as the accelerated beams.[9-11] In the wake type accelerators so far proposed the physical boundary between source, coupling and structure components is indistinct. That is also the case for at least one of the proposed laser driven[6] accelerators, shown schematically in Figure 5, in which the structure is inside the laser cavity. While it has been shown[3] that this particular form is not suitable for accelerating relativistic particles, modification of the laser cavity arrangement and grating could, in principle, make the system workable. An example of an integrated cavity-grating system that does work is sketched in Figure 6 and has been used in the inverse manner to produce mm waves from a beam traversing



GRATING MOUNTED ON ONE MIRROR OF LASER CAVITY
FIG. 5

the grating.[12] A laser driven, near field grating accelerator in which source, coupling and structure are physically distinct[5] is shown schematically in Figure 7.

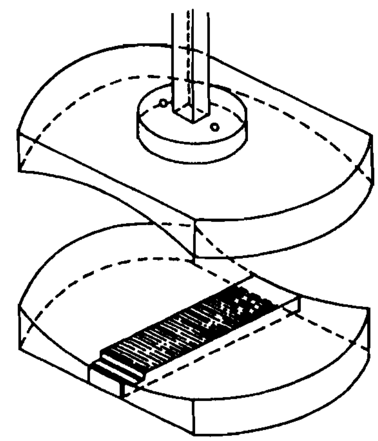


FIG. 6

This generalized manner of describing some of the various near field accelerators that have been suggested, makes it clear that they are, by and large, collective accelerators and that the various manifestations represent various engineering approaches to the same problem. The problem is to extract, through some collective interaction, the power carried by one or more relatively massive beams to a relatively less massive collection of individual particles through the agency of longitudinal EM fields which can exist in vacuo near the surfaces of conductors and dielectrics. A wide variety of possibilities has been shown to exist; more will be discovered. Our challenge is to find a technically possible combination of these elements which will yield an economically viable accelerator system for TeV range energies and then to develop the requisite technology. Reviews of many of the systems proposed to date can be found in the references.

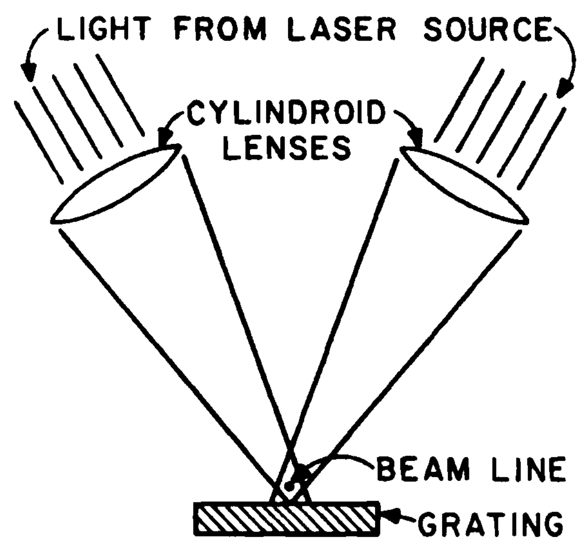


FIG. 7

Performance Requirements

A useful accelerator system for next generation particle physics will have to have, by present standards, high capital and thermodynamic efficiencies, since currently envisioned accelerators are already taxing our budgetary and electric power resources. In addition, of course, the luminosity of the accelerator system will have to exceed some minimum value to produce useful science. This minimum is, unfortunately, ill defined.

The required capital efficiency will depend upon the type of particle accelerator and the kind of physics being addressed. If it is the energy per "elementary" beam particle that is important, and about 1 TeV per elementary beam particle is our goal, then a capital efficiency of 1 GeV/M$ for electron machines and 10 GeV/M$ for proton machines might be taken as rough lower limits for acceptable cost efficiency. So far, only circular proton machines seem within gunshot of these goals although even that may prove illusory. For linac type devices it is probably true that achievement of acceptable capital efficiency will entail achievement of considerably higher accelerating gradients (MV/m) than are now achieved in common practice.

The question of required thermodynamic efficiency ultimately boils down to the question of what is the operating power for a given accelerator system. It seems obvious that today a total system power requirement of greater than 100 MW will be socially unacceptable. Since current and planned facilities are already very close to or at this limit, it seems clear that we will have to do much better than we do now both in terms of GeV/MW and in terms of luminosity/MW. A detailed discussion of this subject must focus on a particular accelerator system. In discussing performance limitations, we will see that for at least one type of near field linac system, the efficiency of conversion of AC input power into beam power will need to be at least of the order of 10% to be acceptable and that meeting this challenge will require considerable technological development.

A discussion of luminosity requirements or limitations is beyond the scope of this treatment. Much of what is known is presented in the proceedings of the two ICFA workshops and elsewhere in these proceedings. Suffice it to say that, as far as is known, near field type linac systems are as luminosity capable, in principle, as any other proposed system and that any currently envisioned technology is likely to be limited to luminosities below $10^{33}cm^{-2}sec^{-1}$.

Performance Limitations

Gradient Limits

The gradient limits for near field normal conducting structures are poorly understood. One physical mechanism which can lead to effective gradient limitation is ionization and acceleration of surface adsorbed gas leading to severe sparking. Detailed measurements on this phenomenon have been made only up to frequencies of about 3 GHz. The limit is not a hard one as it depends upon detailed surface conditions. The general result is that $E_{max} \propto \sqrt{f_{rf}}$ and that present vacuum and surface preparation technology may limit achievable accelerating fields to about 100 MV/m at 3 GHz. As the frequency is raised to avoid this problem other mechanisms come into play. Ultimately the imposed fields will ionize the surface layer and the resultant charge cloud will reflect the incident radiation, limiting the field in the near zone even if surface damage to the structure is of no consequence. A thorough theoretical treatment of the processes involved has yet to be made. One approximate treatment[13] indicates that effective accelerating fields of a few GV/m may be possible, provided that the incoming radiation need be incident for no more than a few picoseconds. Such filling times are compatible with operating wavelengths shorter than a few tens of μ. If surface damage to the structure must be avoided, then melting of the surface may set a somewhat lower limit to the peak fields allowed. A straightforward computation of this effect[14] shows that the limiting incident power density is proportional to the square root of the pulse length. For accelerator application this leads to the conclusion that $E_{max} \propto \lambda^{-1/8}$ and that at a wavelength of 10μ the field will be limited to about 1 GV/m. Experimental studies of laser damage to polished copper mirrors[15] and other materials indicate that the computation of the melting limit is correct at least down to pulse lengths of 100 ps. The threshold for creation of significant surface ionization seems to be below that for melting in these studies[16], but the pulse lengths used in the studies is much larger than appropriate for accelerator applications and the time resolution of the experiments is not fine enough to explore the transient regime of plasma formation.

Thermodynamic Efficiency Limitations

Any quantitative discussion of efficiency must concern itself with a particular accelerator system and mode of operation of that system. Many of the possible systems alluded to are at too early a stage of development for reliable estimation of their potential efficiencies. As an illustrative example, therefore, we pick a system, which is relatively well understood, the microwave linac. Similar considerations will be important for any near field linac system. Advanced development of this type of system could lead to an economical system for electron physics in the TeV domain. Efficiency factors for this system have been presented thoroughly and clearly elsewhere[17] so the results only will be quoted here. We shall assume that, as in the reference, the system is to be operated in the single pass, single bunch mode at microwave frequencies. The overall efficiency has several components, as it would in any complex system.

$$\eta_T \equiv \frac{P_{beam}}{P_{ac}} = \prod_{i=1}^{n} \eta_i$$

η_1 = ac-dc conversion η

η_2 = dc to rf conversion η

η_3 = coupling (losses between source and structure)

η_4 = η of conversion of input rf to stored energy in the structure

η_5 = η of conversion of stored energy in structure to beam kinetic energy

$\underline{\eta_1}$: AC-DC conversion efficiencies are now quite good. It is probably safe to assume that one can achieve 97% or better.

$\underline{\eta_2}$: DC to rf conversion efficiency, for short pulse tubes including klystrons is about 25% today. Since long pulse tubes can have $\eta_2 \simeq 70\%$, one might guess that by use of relativistic beams and sophisticated bunching techniques one might reach $\eta_2 \lesssim 85\%$ after considerable effort.

$\underline{\eta_3}$: Waveguide coupling networks can be quite good. 90% is probably achievable.

η_4 : This quantity, called the structure efficiency, is directly related to the amount of field multiplication demanded of the structure. The more multiplication, the lower the efficiency due to increased dissipation in the structure. Low multiplication corresponds to high group velocity and high peak input power. In common structures today V_g = 0.01c with $\eta_4 \simeq 0.6$, requiring 1.6 GW to achieve 100 MV/m acceleration. New structure designs may have V_g of 0.1 to 0.2c with $\eta_5 \sim 0.8$ and requiring several GW peak power to achieve 100 MV/m.

η_5 : This quantity, called the beam efficiency, is the ratio of energy gain per unit length to energy stored per unit length of structure.

$$\eta_5 \equiv \eta_b = \frac{\omega^2 N_b K_s}{E_a}$$

where ω is the operating frequency, N_b is the number of charges in the bunch being accelerated, E_a is the effective accelerating field and K_s is a constant which characterizes the coupling strength between beam and accelerating mode for a given structure geometry. Clearly we need to accelerate as many charges per bunch as possible to have good energy transfer efficiency.

Unfortunately, N_b is limited through the interaction of the bunch with higher order accelerating and deflecting modes of the structure. This interaction between the bunch and its own electromagnetic wake tends to dilute the phase space density of the beam and is thus inimical to good luminosity. Both relative energy spread and transverse emittance are enlarged by the beam-wake interaction:

$$\frac{\Delta E}{E} \propto \frac{N\omega^2}{E_a} K_{LS}$$

$$\frac{\Delta X}{X} \propto \frac{N\omega^3 \lambda_\beta}{E_a} K_{TS}$$

where K_{LS} and K_{TS} are beam-structure coupling constants characteristic of higher order longitudinal and transverse (accelerating and deflecting) modes and depend upon structure geometry. λ_β is the wavelength characteristic of the (externally imposed) transverse focusing system. ω is the rf radian frequency. If λ_β is made to scale as ω^{-1}, the two phase space diluting terms have the same dependences. Thus the maximum tolerable phase space dilution will set an upper bound for $\frac{N\omega^2}{E_a}$ and thus for η_b. For structures now in use, $\eta_b < 1\%$ (one bunch accelerated). It seems possible to design new structures for which the K_s's are more favorable leading to $\eta_b \lesssim 10\%$. Naturally if we can learn to use multiple bunches of differing energies, this efficiency can be made much better.[7] We can now perform the computation for the overall efficiency putting in the lower and upper efficiency numbers just discussed,

$$\frac{P_b}{P_{ac}} \equiv \eta_T \simeq (0.97)\times(0.25\text{-}0.85)\times(0.95)\times(0.6\text{-}0.8)\times(0.01\text{-}0.1)$$

$$0.001 < \eta_T < 0.06 \qquad \text{(one bunch only)}$$

Whether the maximum efficiencies noted can be achieved simultaneously, especially in a structure which can support the highest possible gradients, is very much an open question.

To compute the total AC power required one must know the ratio of luminosity to beam power which is impossible to determine with precision given our ignorance of how well single pass colliders will work. Given the best figures available one might guess that a minimum desirable luminosity for a 1 TeV electron machine might be $10^{33}cm^{-2}sec^{-1}$ and that a beam power of 10 MW may be needed for its achievement. This means that input power of 100 MW would be needed if $\eta_T \approx 10\%$. Thus we see that while the microwave linac system may come within reach of the overall efficiency goal, considerable development work lies ahead.

Parallel considerations will apply to any proposed near field system, and need to be considered as part of the initial design along with gradient capability.

Operating Wavelength

We have seen that the drive for higher gradients may benefit from use of shorter operating wavelengths. If the accelerator is to be used in the collider mode, there may be other benefits and constraints connected with shorter wavelengths. Any detailed discussion of this matter must refer to a specific design. As illustrative of the considerations involved, we can work again with a scaling of the cylindrical, iris loaded, waveguide accelerator[17] used in the single pass collider mode with electrons. As discussed in the section on efficiency, the maximum number of charges per bunch as a function of wavelength is constrained by the simultaneous need for small emittance growth on the one hand and reasonable beam efficiency on the other. In using the accelerator in the collider mode, further constraints on beam shapes and density are encountered. These constraints are imposed by the beam-beam interactions and are commonly characterized by the "disruption parameter" D and the beamsstrahlung" parameter parameter δ.[18] Without much loss of generality we can consider the case of beams which are uniform, elliptical rods of charge with dimensions σ_H, σ_V, σ_L. We will assume that the phase space areas associated with these dimensions, E_H, E_V, $\Delta E \Delta t$ are of uniform density and uncoupled. The basic collider equations are then:[19]

$$L = M \frac{N^2 f}{4\pi\sqrt{E_H E_V \beta_H^* \beta_V^*}} \leq L_o \qquad (1)$$

$$D = \frac{r_o \sigma_L N R}{\sqrt{E_H E_V \beta_H^* \beta_V^*}\,(1+R)\gamma} \geq D_o \tag{2}$$

$$\delta = \frac{4}{3\sqrt{3}} \frac{r_o^3 N^2 \gamma R}{\sqrt{E_H E_V \beta_H^* \beta_V^*}\,(1+R)^2 \sigma_L} \leq \delta_o \tag{3}$$

N = number of charges per bunch

f = repetition rate

r_o = classical electron radius

γ = beam Lorentz factor

$R = \sigma_H^*/\sigma_V^*$

$*$ refers to collision point

β's = usual focusing parameters

L_o, D_o are reference minimum values

δ_o is the maximum allowed value of fractional energy spread incurred by radiation during the collision

M = multiplying factor believed to apply when self pinching of e^+e^- beams increases density at crossing point.

The efficiency-stability constraint can be expressed as $N = K\lambda^2 E_a$ with provision that $\lambda_\beta \propto \lambda$ in the main body of the accelerator. Inserting this relation into (2) and (3) we obtain:

$$D: \quad \frac{(1+R)}{R} \sqrt{E_H E_V \beta_H^* \beta_V^*} \leq \frac{r_o K}{\gamma D_o} \sigma_L \lambda^2 E_a \tag{4}$$

$$\delta: \quad \frac{(1+R)^2}{R} \sqrt{E_H E_V \beta_H^* \beta_V^*} \geq \frac{4}{3\sqrt{3}} \frac{r_o^3 K^2 \gamma}{\delta_o} \frac{\lambda^4 E_a^2}{\sigma_L} \tag{5}$$

For the case we have chosen, that of the <u>single</u> bunch, single pass, electron collider, $\sigma_L = F\lambda$ where $F << 1$ to keep small energy spread, (4) and (5) then simplify to:

$$\frac{(1+R)}{R} \sqrt{E_H E_V \beta_H^* \beta_V^*} \leq \frac{r_o KF}{\gamma D_o} \lambda^3 E_a \tag{6}$$

$$\frac{(1+R)^2}{R} \sqrt{E_H E_V \beta_H^* \beta_V^*} \geq \frac{4}{3\sqrt{3}} \frac{r_o^3 K^2 \gamma}{\delta_o F} \lambda^3 E_a^2 \tag{7}$$

The best we can do as λ is varied to much smaller values is to maintain the equalities implied by (6) and (7) in response to changes in λ and E_a. Changing (6) and (7) to equalities and dividing (7) by

(6), we see that we shall need to vary the beam aspect ratio according to the rule

$$1 + R = \frac{4}{3\sqrt{3}} \frac{r_o^2 K D_o \gamma^2}{\delta_o F^2} E_a = A \cdot E_a \tag{8}$$

So, we need to engineer the aspect ratio in accordance with (8) and the emittances and focusing at the crossing point to satisfy (6) or (7) taken as equalities. One possible solution which gives the mildest possible λ dependence for the engineered parameters has

$$E_H \propto R\lambda^2; \; E_V \propto \lambda^2; \; \beta_H^* \propto R\lambda; \; \beta_V^* \propto \lambda \tag{9}$$

Note that the β's can vary no faster than λ as we must always maintain the inequality $\beta^* > \sigma_L$. Also remember that our stability condition demands that along the length of the accelerator we must maintain $\beta_{H,V} \propto \lambda$.

From (9), $\sigma_H^* \propto R\lambda^{3/2}$, $\sigma_V^* \propto \lambda^{3/2}$. Conditions (9) and our assumed condition that $\sigma_L = F\lambda$ also have important implications for the required beam brightness.

$$N \equiv B \iiiint\!\!\iint d^2E_H \, d^2E_V \, d^2E_L$$

where B is the phase space density of the beam or brightness. Carrying out the indicated operations constrained by the various assumptions and considerations above we find that the brightness of the source must be engineered such that

$$B \propto \frac{(1 + R)}{R} \lambda^{-3} \tag{10}$$

Combining (1), (6) and $N^2 = \lambda^4 E_a^2 K^2$ we find the repetition rate, f, to be:

$$f = \frac{4\pi r_o F L_o}{M\lambda E_a \gamma D_o K} \frac{R}{(1 + R)} \tag{11}$$

and the total beam power is required to be:

$$P_b = 2Nef \cdot mc^2\gamma = \frac{8\pi e r_o m_o c^2 F \lambda L_o}{MD_o} \frac{R}{(1 + R)} \tag{12}$$

In other words, if the stringent engineering requirements discussed above can be met, there is a beam power, and thus total power, advantage to be gained from operations at smaller λ.

It has been suggested[20] that another mode of operation in which σ^* is kept constant, is possible. This would allow constancy of the β^*'s as λ is reduced and would require that the charge bunch be accelerated as a series of microbunches, keeping the total charge per acceleration cycle constant. Debunching at the end would form the colliding packets but must be done without introducing an increased energy spread due to synchrotron radiation fluctuations. Some "active" debunching might be used to reduce the energy spread at the final focus. Complete assessment of this suggestion will necessitate a reanalysis of the efficiency-stability condition. If this condition remains about the same, the rep. rate would vary as λ^{-2} for constant L and the average beam power would be constant. The beamsstrahlung would be greatly relieved at the price of the higher rep. rate. Some compromise between the two modes of operation discussed above might be necessary or desirable.

Required R/D Work

R/D required for some specific near field accelerators is described elsewhere in these proceedings and will not be considered further here. Generally speaking, extensive R/D in sources, coupling networks and structures is needed.

Sources

With the possible exception of those needed for the wakefield accelerator, none of the sources needed for TeV class linacs now exist. In the microwave region, one to several GW (peak) amplifiers are needed and a number of interesting possibilities have been suggested[7,21] including multiple beam klystrons, klystrons plus Q-switched storage devices, photo-modulated relativistic beam tubes and relativistic proton beams. Amplifiers in common use today have 10's of MW output. One or two experimental tubes have made very short pulses with about 1 GW, peak. We are far from having the needed source device in hand. At the short λ end of the microwave spectrum, a modest development effort to produce a free electron laser source for linac service is underway.[8] At very short wavelength, lasers have been mooted as ideal sources. While it is true that lasers with the requisite peak powers have been demonstrated, no device of the required short pulse length and coherence has been developed. A sample of typical high power laser characteristics is given in an appendix. Note that none of these devices has a repetition rate suitable for accelerator service. The efficiencies are also low. Concerted development efforts might remedy these serious deficiencies. If particle physicists are serious about trying to develop a laser driven accelerator, it seems clear that they will have to be involved in the development of the lasers needed for the job.

Coupling Networks

In the microwave region, suitable coupling means probably exist already or can be developed quickly. This is not true for wavelengths in the mm region and below where only the most sketchy conceptual designs, if any, exist. Much firmer structure designs must be in hand before serious attention can be given to the needed coupling networks.

Structures

This area is wide open, with many directions that need investigating. While one may be tempted to reject dielectric loaded near field structures out of hand because of the relatively low internal breakdown fields in solid dielectrics[22] ($70 \leq E \leq 700$ MV/m), their potential simplicity makes further investigation seem worthwhile.

Several areas in conducting near field structures need work. No general algorithm exists for optimizing wakefield performance of structures in relation to performance in the accelerating mode. Optimization will involve variation of structure profile shapes and computation of the K's for families of shapes. In addition, we must add the conditions for good structure efficiency and low peak to average field ratios to the consideration. Many of the elements of the calculational tools needed to do this job are in hand. Integrating them into a useful whole and exploiting them for study of existing classes of structures and for inventing new, better structure types will be a formidable challenge.

A matter of great importance is the exploration of limiting fields as a function of frequency and pulse length. A systematic study for $\lambda \leq 3$ cm would be of great help in deciding on the optimum frequency. Sources of sufficient peak power for useful tests exist in the band, $\lambda \leq 3$ mm and again for $\lambda \leq 10\ \mu$. While mirror damage studies in the infrared give useful information, accelerator field limits will depend on some factors other than those included in the mirror damage studies. We need to make time resolved measurements of surface damage, plasma formation and reflectivity in which the influence of the electric field component perpendicular to the surface can be studied independently. Lasers and optical elements suitable for such studies do exist now but must be applied to the job.

Considerations so far have emphasized near field accelerators utilizing normal conducting structures. Superconducting structures may also be useful. In a recent review article[23] it was shown that rf superconductivity can be a candidate technology for TeV class accelerators only if the theoretically possible loss and surface field strength limits can be achieved in large scale devices. Required performance levels have been achieved in small scale devices.

Beam Optics and Particle Sources

Many of the accelerator systems included in the above discussion will require the use of micron or sub-micron sized beams. Considerable R/D on the technology of guiding and focusing systems for such beams will be needed. It is also not clear that particle sources of the required brightness now exist. Extensive work on this area may be required.

Summary

I have tried to indicate that from among the array of near field linear accelerating system possibilities we may be able to find a candidate suitable for attack on the next frontier of particle physics. It is far from a sure bet that this will be the case. Particle physicists and institutions devoted to the opening of this frontier will need to make considerable commitments, both personal and institutional, to the development of the requisite accelerator technology.

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(a) Calculated from the transform limit, unless marked with (b). This gives the most optimistic coherence length possible for that pulse duration.

(c) Free-electron lasers can run at almost any wavelength; this example was chosen to illustrate possibilities in the FIR. Note also that this is the only laser on the list that can be described as having a rep rate, probably about 30 Hz.

NOTE: All of these data are open to debate, even those for systems that are in operation. This list is our best effort to provide numbers that might be obtained in reality.

A SAMPLER OF LARGE LASER SYSTEM CHARACTERISTICS[24]

This is an incomplete (and parochial) but representative listing of the characteristics of large laser systems at a variety of wavelengths. Presently operating, under construction, and reasonably foreseeable systems are included.

LASER	TIME SCALE	TYPE	WAVELENGTH	ENERGY (per shot)	PULSE LENGTH	PULSE POWER.W	BRIGHTNESS ($W/cm^2/sr$)	LINE WIDTH[a]	COHERENCE LENGTH[a]
Planned Los Alamos	Future	Free-Electron	200 μm[c]	30 mJ	30 ps	10^9	10^{12}	30 GHz	1 cm
HELIOS Los Alamos	Operating	CO_2	10.6 μm	9.5 kJ	.75 ns	$1.3x10^{13}$	$2x10^{17}$	1.3 GHz	25 cm
ANTARES Los Alamos	Near Future	CO_2	10.6 μm	40 kJ	.60 ns	$7x10^{13}$	$2x10^{17}$	1.7 GHz	18 cm
Concept Los Alamos	Future	CO_2	10.6 μm	1.25 MJ	10 ns	$1.25x10^{14}$	$5x10^{17}$	100 MHz	3 m
OMEGA U. Rochester	Operating	Nd:Glass	1.06 μm	600 J	50 ps	$12x10^{12}$	$4x10^{17}$	10 GHz	3 cm
NOVETTE Livermore	Near Future	Nd:Glass	1.06 μm	20 kJ	1 ns	$2x10^{13}$	$2x10^{17}$	1 GHz	30 cm
NOVA Livermore	Future	Nd:Glass	1.06 μm	100 kJ	1 ns	10^{14}	10^{18}	1 GHz	3 cm
OMEGA U. Rochester	Future	Tripled	355 nm	450 J	50 ps	$9x10^{12}$	$3x10^{18}$	10 GHz	3 cm
RAPIER Livermore	Operating	KrF	248 nm	50 J	40 ns	$1.25x10^9$	$5x10^{17}$	500 MHz[b]	60 cm[b]

DISCUSSION

(There was an initial extensive and rather confused discussion about various detailed matters arising from the talk, including the constraints imposed by wake fields, much of which is only intelligible in conjunction with the transparencies. Points raised should be clear from the written paper, and relevant papers in the proceedings of the Los Alamos meeting).

Tigner. Suppose I have a collider which works at 10 cm with 100 MV/metre gradient, and 100 Hz repetition rate to get the required luminosity. Then, using the intensity scaling relationship, ω^2/accelerating field, if I want to operate at 10 μ and can get 500 MV/metre I would need a repetition rate of 2×10^7 Hz to get the same luminosity.

Pellegrini. This restriction of the luminosity arises in near field accelerators. In far field laser accelerators these wakes do not exist, and the scaling of luminosity can be completely different.